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EFFECT OF STRESS ON THE MAGNETIC PROPERTIES OF STEEL WIRE

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ABSTRACT

The work here described is a part of a more extended investigation on nondestructive methods of testing wire rope. Data are given in terms of magnetic reluctivity showing the effect of stress on the magnetic properties. It is found that the reluctivity, which is a linear function of the magnetizing force for pure homogeneous materials, no longer shows such a linear relationship when tension is applied to the wire. It is shown how two components of the material differing only as regards stress condition and each following the linear relationship can be combined to give the results found by experiment. This method of analysis seems to be capable of further development and extension into other fields of magnetic analysis.

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I. INTRODUCTION

It has long been known that mechanical stress has a marked influence on the magnetic properties of iron and steel. Many investigations of this effect have been carried out and its general nature is very well understood. It is doubtful, however, whether the disturbing influence of this factor in the attempt to establish definite correlations between magnetic properties and other physical properties has hitherto been sufficiently well recognized. Although the disturbing effect of stress on the magnetic properties is most marked for moderate values of magnetizing force, it is within this range that a majority of the researches on correlation of magnetic properties with effects other than stress have been made. Figure 1 illustrates the effect of a relatively moderate degree of tension on the magnetic permeability of steel wire, such as used in the manufacture of wire rope.¹

¹ The work here described is part of a more comprehensive investigation on nondestructive methods for testing wire rope. In view of the difficulty in the interpretation of results encountered in previous investigations of a similar nature, a study is first being made of the effects on the magnetic properties of various causes of deterioration in wire rope.

In view of the fact that the permeability at a given value of magnetizing force may be nearly doubled by the application of a small amount of stress, it is not difficult to understand that the effect of various other factors, such as chemical segregations or changes in metallographic structure, on the magnetic properties may be entirely masked by residual stress effects resulting from mechanical work or heat treatment during the process of manufacture. It is obvious, therefore, that, in any satisfactory method

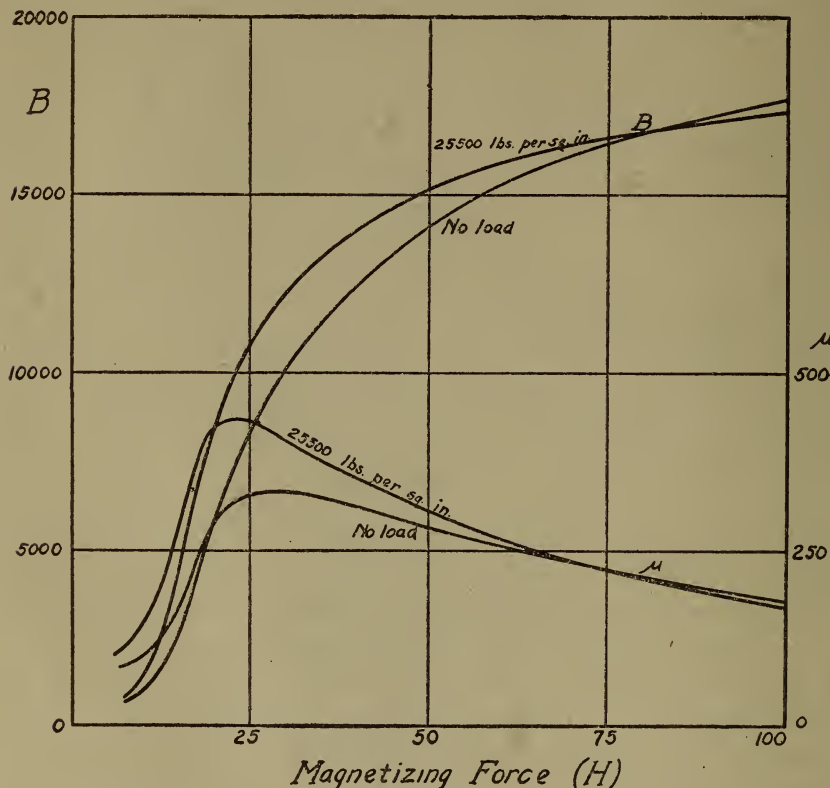


FIG. 1.—Effect of mechanical stress on the magnetic properties of steel

of magnetic exploration for the detection of flaws and imperfections, either the indications of the instruments must be independent of the effect of stress or a method must be available for evaluating this effect so that it can be eliminated from the results. Up to the present time no magnetic method for the detection of flaws and imperfections has been described, the results of which are unambiguous and free from the difficulties just mentioned.

The object of the present investigation was to establish, if possible, a quantitative relationship between stress and magnetic

properties in the hope of discovering some method by which the effects of stress can be properly taken into account. Although but a single special case has been covered, a method of analysis has been worked out, which seems to warrant further study and application in other cases and consequently is described at this time.

II. THE RELUCTIVITY RELATIONSHIP

Although the effect of stress is greatest at moderate values of magnetizing force, it is not easy to make a quantitative study of its magnitude in this range because there is no adequate method of expressing the magnetic properties in terms of a simple mathematical formula. For this reason, observations were made at high magnetizing forces in the range covered by Kennelly's law.² This law, which has been referred to as the reluctivity relationship shows a linear relationship between metallic reluctivity and magnetizing force and is expressed as follows:

$$\rho = \alpha + \beta H$$

in which

$$\rho = \text{metallic reluctivity} \left(\frac{H}{B-H} \right)$$

$$H = \text{magnetizing force}$$

$$\alpha \text{ and } \beta = \text{constants characteristic of the material.}$$

Above a certain minimum value of magnetizing force this law has been found to hold for pure homogeneous materials. It is to be noted that metallic induction ($B-H$) and metallic reluctivity $\left(\frac{H}{B-H} \right)$ must always be used in the expression of this relation which is shown graphically in Figure 2.

β is the slope of the reluctivity line and its reciprocal can be shown to be equal to the saturation value of the metallic induction.

$$\frac{1}{\beta} = (B-H)_{\max}$$

α is the intercept of the line on the reluctivity axis and, since it indicates the rate at which magnetic saturation is approached, has been termed the "coefficient of magnetic hardness." α and β , then, may be properly considered as magnetic constants for pure, homogeneous material.

For impure or inhomogeneous materials the reluctivity graph departs from a straight line by an amount depending upon the

² Kennelly, Am. Inst. Elec. Eng. Trans., 8, p. 485; 1891.

degree of impurity or inhomogeneity. This departure from a straight line has been experimentally investigated by Ball,³ who demonstrated that the departure was due to the presence of two or more magnetically different components. Ball further concluded that the reluctivity line resulting from two or more different constituents could be represented as a number of straight portions, each having a definite value of α and β . This conclusion is not verified by the results of the present investigation, and will be discussed in more detail later.

In view of the simple nature of the mathematical expression and of the other facts just referred to, it appeared that the most

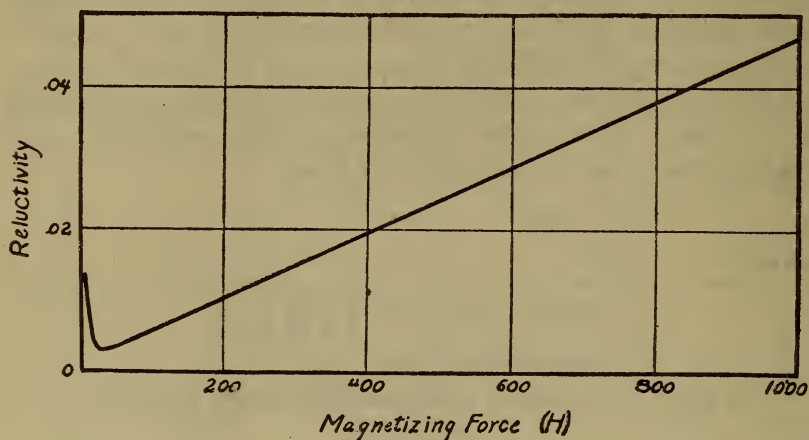


FIG. 2.—Magnetic reluctivity relationship

promising and logical approach to the problem in hand was by way of the reluctivity relationship which has already been found useful in the study of the effect of heat treatment.⁴

III. OBSERVATIONS AND RESULTS

In order to study the magnetic properties of steel wire in the light of the reluctivity relationship it was necessary to provide for the application of magnetizing forces up to 1,000 gilberts per centimeter. For this purpose a special solenoid 50 cm long was wound on a fiber form. The winding consisted of 10 layers of No. 17 silk-enamel wire which would carry 10 amperes for a short time without undue heating. The concentration of the winding was such that the magnetizing force was approximately 100 times the current in amperes. The ordinary ballistic method was used, the test coils of 100 turns each being wound directly on the wire.

³ Ball, *Jour. Frank. Inst.*, 181, p. 459; 1916.

⁴ Nusbaum, Cheney, and Scott, *B. S. Sci. Paper*, No. 404; 1920.

Since the wire was only 2.54 mm (0.1 inch) in diameter the dimensional ratio was over 200 so that the demagnetizing factor was so small as to be negligible. The ballistic galvanometer used had a large external resistance for critical damping and sufficient sensitivity so that it could be used in a heavily overdamped condition, thus giving practically fluxmeter performance. Calibration was by means of a standard mutual inductance whose secondary was kept always in the galvanometer circuit.

The wire under test was placed in a Scott horizontal testing machine of 2,000 pounds capacity with the magnetizing solenoid surrounding it, and normal induction data obtained for various values of applied tension. The material tested consisted of samples of four grades of steel wire, commonly used in the manufacture of wire rope, 0.1 inch in diameter.⁵ In view of the fact that the results were of a similar nature for all of the grades of wire tested, and, also, that the primary object of this paper is to describe a method of analysis of the results rather than to present data for various kinds of material, the results reported are only those obtained for the highest grade known as Monitor, which has an ultimate strength as given by the manufacturers of from 240,000 to 260,000 lbs./in.²

TABLE 1.—Values of Reluctivity $\left(\frac{H}{B-H}\right)$ for Various Loads for Monitor Steel Wire

[Tension in pounds per square inch]

H	0	25,500	38,250	51,000	63,750	76,500	89,250	102,000
100.....	0.00634	0.00628	0.00631	0.00630	0.00631	0.00633	0.00637	0.00640
200.....	.01105	.01106	.01111	.01115	.01122	.01128	.01136	.01144
300.....	.01574	.01582	.01586	.01592	.01598	.01609	.01622	.01631
400.....	.02040	.02050	.02058	.02064	.02074	.02084	.02095	.02110
500.....	.02513	.02522	.02530	.02538	.02546	.02554	.02568	.02580
600.....	.02981	.02994	.02997	.03010	.03020	.03024	.03038	.03050
700.....	.03444	.03461	.03461	.03478	.03481	.03496	.03501	.03513
800.....	.03925	.03938	.03940	.03944	.03957	.03964	.03975	.03982

In Table 1 are given the values of metallic reluctivity $\left(\frac{H}{B-H}\right)$ calculated from the observed normal induction data for values of tension up to 102,000 lbs./in.² Values are not given for magnetizing forces below 100 as the linear relationship does not hold for the lower part of the curve. The effect of stress is to cause a departure from the linear relationship, the departure becoming

⁵ This wire was kindly furnished by the American Steel & Wire Co.

greater as the tension is increased. This deviation⁶ is shown in Figure 3, in which is shown the difference between ρ and βH ($\Delta = \rho - \beta H$). The curves here given also demonstrate the fact, already mentioned, that the reluctivity curve for inhomogeneous material can not be considered to be made up of a number of straight portions with sharp breaks, but that it is a continuous curve. If there were really a sharp break this Δ curve would rise to a sharp maximum, after which the values of Δ would decrease. Several reluctivity curves taken from the results of other investigations have been examined by this method, and in none of them is a sharp break to be observed.

IV. THEORY

For purposes of discussion and analysis of the results let us make some assumptions which appear to be valid in this case and see if the observed data bear out the resulting theory.

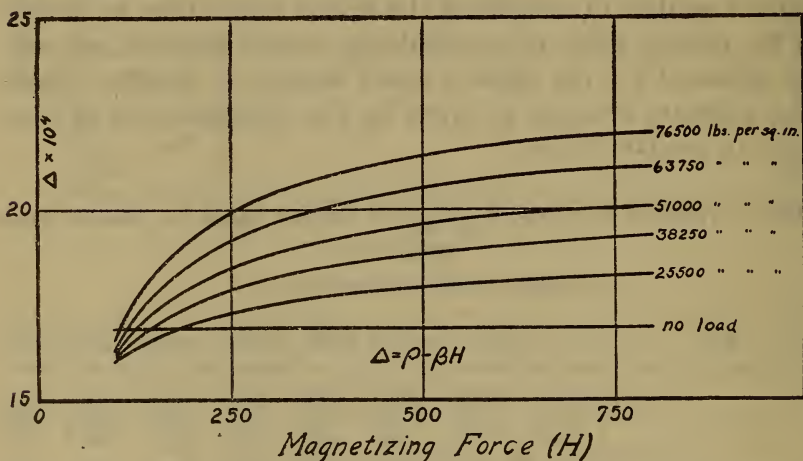


FIG. 3.—Deviation from a straight line, parallel to the asymptote but passing through the origin, of the reluctivity curves for various degrees of tension

(1) Since the magnetic inhomogeneity causing the departure of the reluctivity relationship from the linear is caused by, and increases with, the degree of tension, the material must be made up of a number of components differing only in their condition as regards stress.

(2) This inhomogeneous condition as regards stress must have been present in the wire before the application of an external load, otherwise the reluctivity line would be straight for all values

⁶ Curves of ρ against H are not given since the departure from the linear, though real, is so small that it can not be shown satisfactorily on a small scale.

of load below the proportional limit. The reason that the lack of homogeneity is not noticeable at no load is probably that the proportion of material differing from the rest in stress condition is either very small or the degree of difference is slight.

(3) Since $\frac{1}{\beta}$ represents the saturation value of magnetization, which is proportional to the number of elementary magnets per unit volume, it seems reasonable to assume that this number is not changed by stress, and consequently that β is the same for all the components.

(4) Since the distribution of stress is probably the result of the drawing operation during the process of manufacture of the wire, it may be assumed that the outside portion is in a state of longitudinal tension balanced by compression in the inner part.

(5) If the stresses are mainly longitudinal then the components differing in magnetic properties are in parallel.

(6) For stresses below the proportional limit there are only two kinds of material, that in tension and that in compression.

Let us assume two components whose magnetic properties can be represented in terms of reluctivity as

$$\begin{aligned}\rho_1 &= \alpha_1 + \beta H \\ \rho_2 &= \alpha_2 + \beta H\end{aligned}\tag{1}$$

If A_1 and A_2 are the respective proportions of the components and they are in parallel, the resultant reluctivity is

$$\rho = \frac{\rho_1 \rho_2}{A_1 \rho_2 + A_2 \rho_1}\tag{2}$$

Substituting the values of ρ_1 and ρ_2 from equations (1) we have

$$\rho = \frac{\alpha_1 \alpha_2 + (\alpha_1 + \alpha_2) \beta H + (\beta H)^2}{A_1 \alpha_2 + A_2 \alpha_1 + \beta H}\tag{3}$$

If we call

$$C_1 = \alpha_1 \alpha_2$$

$$C_2 = \alpha_1 + \alpha_2$$

and

$$C_3 = A_1 \alpha_2 + A_2 \alpha_1$$

equation (3) reduces to the form

$$\rho = \frac{C_1 + C_2 \beta H + (\beta H)^2}{C_3 + \beta H}\tag{4}$$

which is the equation of an hyperbola whose asymptote is

$$\rho_a = C_2 - C_3 + \beta H$$

or

$$\rho_a = m + \beta H$$

where

$$m = C_2 - C_3$$

Substituting $m + C_3$ for C_2 in equation (4) we find

$$\begin{aligned} \rho &= \frac{C_1 + (m + C_3) \beta H + (\beta H)^2}{C_3 + \beta H} \\ &= \frac{C_1 - mC_3 + mC_3 + (m + C_3) \beta H + (\beta H)^2}{C_3 + \beta H} \\ &= \frac{(m + \beta H) (C_3 + \beta H) + C_1 - mC_3}{C_3 + \beta H} \\ &= m + \beta H + \frac{C_1 - mC_3}{C_3 + \beta H} \end{aligned} \quad (5)$$

If we take δ as the amount that the reluctivity deviates from its asymptote

$$\delta = m + \beta H - \rho = \frac{mC_3 - C_1}{C_3 + \beta H} \quad (6)$$

$$1/\delta = \frac{C_3}{mC_3 - C_1} + \frac{\beta}{mC_3 - C_1} H \quad (7)$$

which is the equation of a straight line from which, if the values of m and β were known, C_1 , C_2 , and C_3 could be evaluated. Then from the values of C_1 , C_2 , and C_3 the values of α_1 , α_2 , A_1 and A_2 can be found from the following relationships:

$$\alpha_1 + \alpha_2 = C_2$$

$$\alpha_1 - \alpha_2 = \sqrt{C_2^2 - 4C_1}$$

$$A_1 = \frac{\alpha_1 - C_3}{\alpha_1 - \alpha_2} \quad (8)$$

$$A_2 = 1 - A_1$$

In the present work the value of β has been taken as the slope of the reluctivity line for no load. It is probable that, if the observations could be made with greater precision, the departure

from a straight line could be noted. With the degree of precision obtainable, however, the deviation appears to be less than the probable error.

If we take Δ as the difference between the reluctivity curve and a line parallel to the asymptote passing through the origin; that is

$$\Delta = \rho - \beta H = m - \delta$$

then it can be shown that

$$\frac{H}{\Delta} = \left(\frac{C_3}{m\beta} - \frac{C_1}{\Delta m\beta} \right) + \frac{H}{m} \quad (9)$$

Since Δ is a variable function of H the resulting graph is not quite a straight line. The quantity in parenthesis, however, is small compared with H/Δ so that the departure from a linear relation is slight and the reciprocal of its slope can be taken as the value of m .

Since the values of δ are small compared with ρ a small error in the determination of ρ can cause a relatively large error in the value of δ . It is difficult, therefore, to obtain satisfactory curves of $1/\delta$ against H . In order to overcome this difficulty an additional relationship was used

$$\Delta/\delta = \frac{C_1}{mC_3 - C_1} + \frac{m\beta}{mC_3 - C_1} H \quad (10)$$

By plotting Δ/δ against H it is possible to test the validity of the assumed law and to determine the values of the various constants.

If it is found by plotting the various functions indicated above against H that straight lines result, we may conclude that, for a first approximation at least, the material may be considered to have two components, one of which is in tension and the other in compression having the respective magnetic properties represented by equations (1) and having the corresponding proportions represented by A_1 and A_2 as calculated by means of the equations given above.

V. ANALYSIS OF EXPERIMENTAL DATA

In Figure 4 are shown the results of plotting values of $\frac{H}{\Delta}$ against H . For loads up to and including 76,500 lbs./in.² the lines are

straight within the limits of experimental error, which indicates that our assumptions are valid within this range. For values above 76,500 lbs./in.² the lines show a distinct curvature. This may be explained by considering that above the proportional limit some of the material has failed mechanically and no longer carries any of the load. It does, however, continue to carry magnetic flux and, therefore, constitutes a third magnetic com-

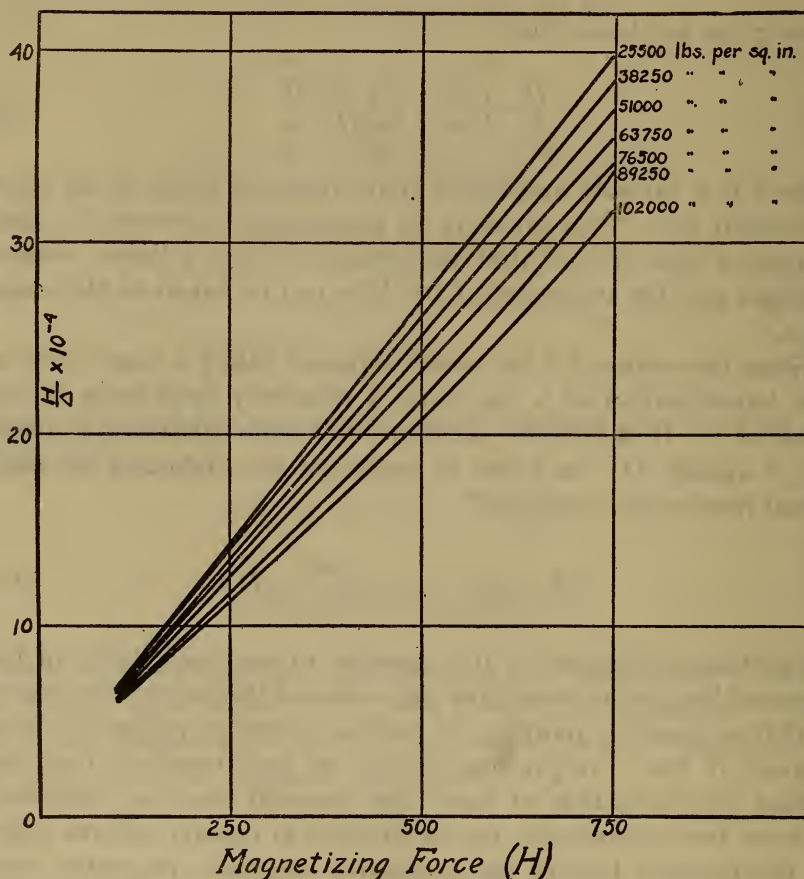


FIG. 4.—Relationship of $\frac{H}{\Delta}$ to magnetizing force for various degrees of tension

ponent. This being the case, the two-component laws can no longer be expected to hold. We conclude, therefore, that the proportional limit has been passed for loads above 76,500 lbs./in.²⁷

Figure 5 shows the variation of m , the intercept of the asymptote of the reluctivity curve, with the load. Within the limits of

⁷ Extensometer measurements indicated about 127,000 lbs./in.² as the proportional limit, but it is thought that the magnetic indications are more sensitive.

experimental error this relationship appears to be a linear one. As before stated the value of β was taken as the slope of the reluctivity line for no load and in this case, is equal to 468×10^{-7} .

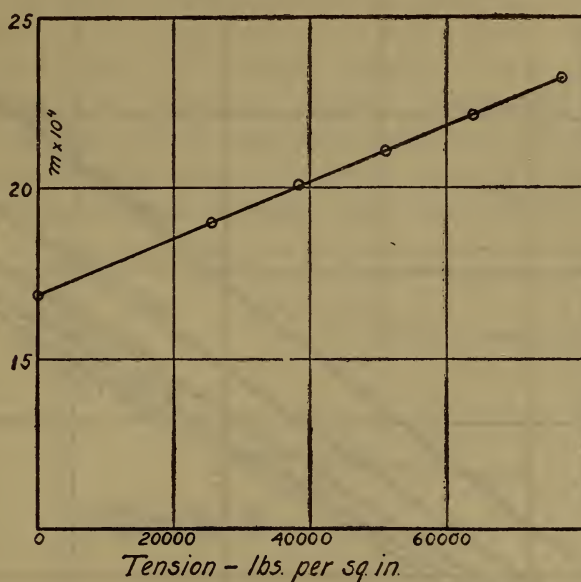


FIG. 5.—Variation of the intercept of the symptote to the reluctivity line for various degrees of tension

In Figure 6 are shown values of Δ/δ plotted against H for stresses below the proportional limit. From these curves the values given in Table 2 were obtained.

TABLE 2.—Constants¹ Calculated From Reluctivity Data for Monitor Steel Wire Under Various Loads

[Tension in pounds per square inch]

	25,500	38,250	51,000	63,750	76,500
m	0.00190	0.00201	0.00211	0.00222	0.00232
a	2.24	1.13	.76	.34	.06
b	.0315	.0275	.0253	.0244	.0239
$C_1 \times 10^6$	6.32	3.81	2.96	1.45	.30
$C_2 \times 10^3$	6.72	5.63	5.37	4.79	4.40
$C_3 \times 10^3$	4.82	3.62	3.26	2.57	2.08
$\alpha_1 \times 10^3$	5.59	4.85	4.75	4.46	4.33
$\alpha_2 \times 10^3$	1.13	.78	.62	.33	.07
A_1	.17	.30	.36	.46	.53
A_2	.83	.70	.64	.54	.47

$$\beta = 468 \times 10^{-7}$$

¹ m determined from the equation $H/\Delta = \left(\frac{C_3 - C_1}{m\beta\Delta m\beta} \right) + \frac{H}{m}$. a and b found from the equation $\frac{\Delta}{\delta} = a + bH$,

where $a = \frac{C_1}{mC_3 - C_1}$ and $b = \frac{m\beta}{mC_3 - C_1}$

$C_1 = \frac{a}{b}m\beta$, $C_3 = \frac{\beta}{b}(1+a)$ and $C_2 = m + C_3\alpha_1$, α_2 , A_1 and A_2 calculated from equations (8) above.

The data of Table 2 are shown graphically in Figure 7. The agreement between the observed values of reluctivity and those

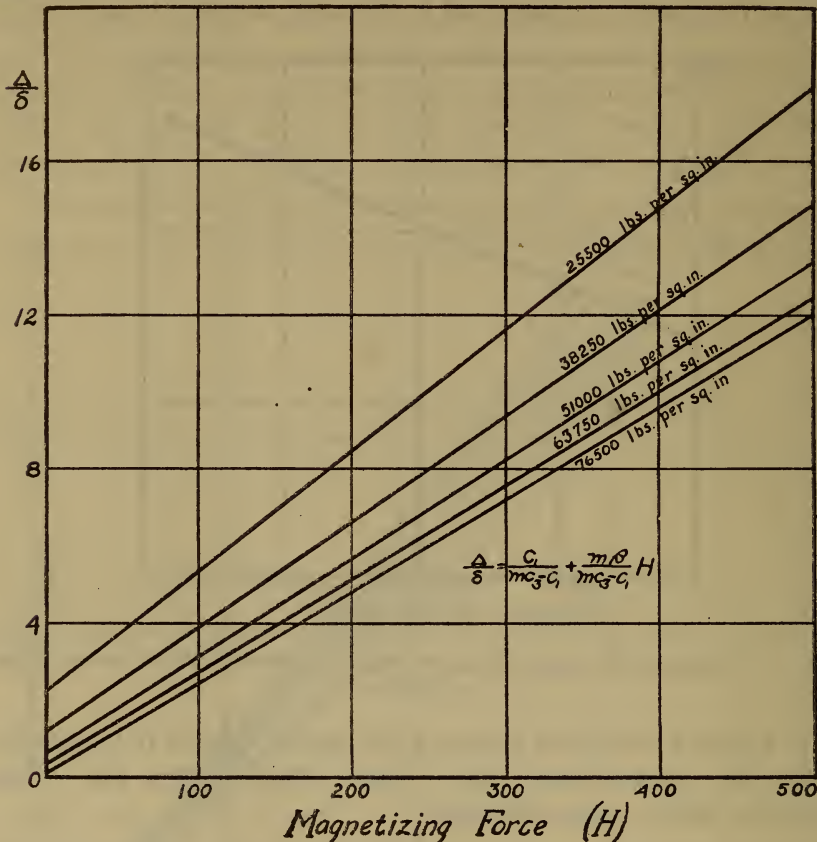


FIG. 6.—Variation of $\frac{\Delta}{\delta}$ with magnetizing force for various degrees of tension

calculated from the constants α_1 , α_2 , A_1 and A_2 is shown in Table 3.

TABLE 3.—Observed and Calculated Values of Reluctivity

[Tension in pounds per square inch]

H	25, 500		38, 250		51, 000		63, 750		76, 500	
	Ob- served	Calcu- lated	Ob- served	Calcu- lated	Ob- served	Calcu- lated	Ob- served	Calcu- lated	Ob- served	Calcu- lated
100.....	0. 00628	0. 00627	0. 00631	0. 00626	0. 00630	0. 00630	0. 00631	0. 00632	0. 00633	0. 00632
200.....	. 01106	. 01105	. 01111	. 01109	. 01115	. 01116	. 01122	. 01122	. 01128	. 01129
300.....	. 01582	. 01578	. 01586	. 01584	. 01592	. 01593	. 01598	. 01601	. 01609	. 01609
400.....	. 02050	. 02049	. 02058	. 02057	. 02064	. 02064	. 02074	. 02075	. 02084	. 02084
500.....	. 02522	. 02520	. 02530	. 02526	. 02538	. 02537	. 02546	. 02546	. 02554	. 02556
600.....	. 02994	. 02991	. 02997	. 02995	. 03010	. 03007	. 03020	. 03019	. 03024	. 03026
700.....	. 03461	. 03459	. 03461	. 03468	. 03478	. 03476	. 03481	. 03485	. 03496	. 03495
800.....	. 03938	. 03927	. 03940	. 03937	. 03944	. 03945	. 03957	. 03958	. 03964	. 03965

The difference between the observed and calculated values of reluctivity is in no case as great as the possible experimental error.

It is not possible from the data here reported to determine the functional relationship between α and stress. This question furnishes a subject for further research. It is apparent that α decreases with increasing tension or decreasing compression. It is, of course, realized that there must be a gradual transition in the material from a state of tension to one of compression, but it appears that the observations have not sufficient precision to

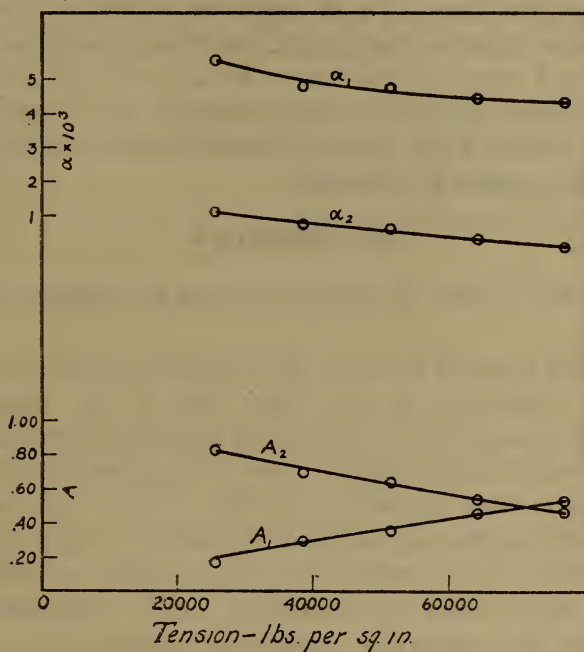


FIG. 7.—Variation of constants α_1 , α_2 , A_1 and A_2 with applied tension

indicate this condition. The values of α and A must be considered as approximations, but it is felt that the results represent the conditions in the main fairly well.

The material under no load is in equilibrium, a small proportion of material under a relatively high degree of tension being balanced by a large proportion of the material under a correspondingly smaller degree of compression. As tension is applied, the proportion of the material in tension increases as well as the relative intensity of the tensile stress as represented by the increase in A_1 and the decrease in α_1 . All of the material has not been brought into a condition of tension until some has actually

failed, thus constituting an additional magnetic component. The mathematical method of solving the reluctivity expression for three components has not been worked out.

It is probable that a further consideration of the phenomena may lead to a better conception of the effect of stress on magnetic properties including the "Villari reversal" and possibly the phenomena of magnetostriction. It is to be understood that this method of analysis so far as it has been developed here applies only to the case of material uniform in magnetic properties except for the influence of stress and in which the parallel arrangement can reasonably be expected to hold. It seems possible, however, that methods might be found of applying the same principles in a more general way. At any rate a field of investigation is opened up which should prove to be of great value in explaining many of the interrelations between magnetic properties and other physical properties.

VI. SUMMARY

The results of this investigation may be summed up briefly as follows:

(1) To the marked influence of mechanical stress on magnetic properties, especially in the steep part of the magnetization curve, may be attributed much of the difficulty heretofore experienced in establishing definite laws of correlation between the magnetic and other physical properties of iron and steel.

(2) In any satisfactory method of magnetic exploration for the detection of flaws in steel it must be possible to eliminate the effects of stress either experimentally or by calculation.

(3) When the reluctivity relationship departs from the linear due to impurities or inhomogeneity the result is not a series of straight lines with sharp breaks, but a continuous curve.

(4) The reluctivity curve for inhomogeneous material is the resultant of two or more straight lines which represent the magnetic properties of the corresponding components making up the material.

(5) If there are only two components, in parallel, and differing only as regards stress conditions, it is possible to calculate the relative proportions of these components and the straight lines representing their magnetic properties by the method here described.

(6) When the applied stress is beyond the proportional limit of the material the laws for two components no longer hold.

(7) Within the proportional limit there is approximately a linear relationship between the applied stress and the intercept on the ρ axis of the asymptote to the reluctivity curve.

(8) Values of reluctivity calculated from the constants obtained by the method of analysis here described agree with the observed values well within the limits of experimental error.

(9) The data and method of analysis here presented open up a new method of approach to the problem of the correlation of magnetic properties with other physical-properties which is worthy of further development and which should yield valuable results in this field.

In conclusion the author wishes to acknowledge the great assistance of Dr. Chester Snow in the development of the mathematical theory and to M. F. Fischer, H. J. Hoyert, and J. M. Barry for the determination of the experimental data and calculation of the results.

WASHINGTON, June 22, 1924.



